DTIC FILE COPY

AD-A223 611

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
FINAL 15 Aug 88 TO 14 Aug 89

4. TITLE AND SUBTITLE
IEEE CONFERENCE OF NEURAL INFORMATION PROCESSING SYSTEMS

5. FUNDING NUMBERS
2305 K5

6. AUTHOR(S)
Professor Terrence Sejnowski

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
John Hopkins University
Dept of Biophysics
Baltimore, MD 21218

8. PERFORMING ORGANIZATION REPORT NUMBER
AFOSR-TR- 90 0719

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
Bldg 410
Bolling AFB Washington DC 20332-6448
Dr. Alan E. Craig

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFOSR-88-0287

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION IS UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

CONFERENCE WAS HELD

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNLIMITED

Abstracts of Papers

1988 IEEE Conference on

NEURAL INFORMATION PROCESSING SYSTEMS — NATURAL AND SYNTHETIC

November 28 - December 1, 1988

Sheraton Denver Tech Center Hotel,
Denver, Colorado

IEEE

1988 IEEE Conference on Neural Information Processing Systems - Natural and Synthetic

November 28 - December 1, 1988

SHERATON DENVER TECH CENTER HOTEL,
DENVER, COLORADO
WITH A POST-MEETING WORKSHOP, DECEMBER 1-3,
KEYSTONE RESORT, COLORADO

Sponsored by:

The Institute of Electrical and Electronic Engineers Information Theory Group, Co-sponsorship with the American Physical Society. A satellite meeting of the Society for Neuroscience. IEEE Groups and Societies involved: Acoustics, Speech, and Signal Processing; Circuits and Systems. Financial support from Bell Communications Research, International Business Machines, Office of Naval Research, Air Force Office of Scientific Research, Army Research Office, and NASA.

ORGANIZING COMMITTEE:

Terrence J. Sejnowski	General Chairman
Scott Kirkpatrick	Program Chairman
Clifford Lau	Treasurer
Jawad Salehi	Publicity Chairman
Kristina Johnson	Local Arrangements
Howard Wachtel	Workshop Coordinator
David S. Touretzky	Publications Chairman
Edward C. Posner	IEEE Liaison
Larry Jackel	Physics Liaison
James Bower	Neurobiology Liaison

PROGRAM COMMITTEE:

Joshua Alspector, AT&T Bell Labs
Dana Anderson, University of Colorado
Pierre Baldi, UCSD
Dana Ballard, University of Rochester
James Bower, California Institute of Techonolgy
John S. Denker, AT&T Bell Labs
Charles Elbaum, Brown University
Walter J. Freeman, UC Berkeley
C. Lee Giles, AFOSR
Ralph Linsker, IBM
Richard P. Lippmann, MIT Lincoln Labs
James McClelland, Carnegie Mellon
John Moody, Yale
Tommaso Poggio, MIT
Daniel Sabbah, IBM
Jay Sage, MIT Lincoln Labs
Allen Selverston, UCSD
Richard Thompson, USC
David Touretzky, Carnegie Mellon
David Van Essen, California Institute of Technology
Santosh Venkatesh, University of Pennsylvania
Hugh Wilson, University of Chicago

PROGRAM HIGHLIGHTS

Monday, November 28,1988

4:00 PM	Registration
8:00 PM	Reception

Tuesday, November 29, 1988

8:30 AM	Oral Session O1: Learning and Generalization Invited talk: Mark Konishi, Caltech, "Birdsong Learning"
9:10 AM	Contributed papers
12:00 PM	Preview Poster Session 1
2:30 PM	Oral Session O2: Applications Invited talk: John Bridle, RSRE, "Speech Recognition"
3:00 PM	Contributed papers
6:00 PM	Beer and chips
8:00 PM	Poster Session 1

Wednesday, November 30, 1988

8:30 AM	Oral Session O3: Neurobiology Invited talk: John Miller, UC Berkeley, "Cricket Wind Detection"
9:10 AM	Contributed papers
12:00PM	Preview Poster Session 2
2:30 PM	Oral Session O4: Structured Networks Invited talk: Geoffrey Hinton, University of Toronto, "Symbol Processing in the Brain"
3:00 PM	Contributed papers
6:30 PM	Reception (cash bar)
7:00 PM	Conference Banquet
9:00 PM	Plenary Speaker: Valentino Braitenberg, Max Planck Institut, "Neural Architecture and Function"

Thursday, December 1, 1988

8:30 AM	Oral Session O5: Implementation Invited talk: Rodney Brooks, MIT, "Programming Robotics"
9:10 AM	Contributed papers
12:00 PM	Poster Session 2
3:00 PM	Adjourn to Keystone for Workshop

Workshop Program (Keystone Lodge)

Thursday, December 1, 1988

8:00 PM Organizational Session

Friday, December 2, 1988

7:30 AM Morning workshop sessions (two hours)

4:30 PM Afternoon workshop sessions (two hours)

8:30 PM Plenary discussion session (two hours)

Saturday, December 3, 1988

7:30 AM Morning workshop sessions (two hours)

4:30 PM Afternoon workshop sessions (two hours)

7:00 PM Banquet

8:30 PM Final plenary discussion (two hours)

Table of Contents

Table of Contents

Table of Contents

Table of Contents

ORAL SESSION O2: APPLICATIONS

ORAL SESSION O3: NEUROBIOLOGY

Table of Contents

POSTER SESSION P2A: NEUROBIOLOGY

Table of Contents

POSTER SESSION P2B: STRUCTURED NETWORKS

POSTER SESSION P2C: IMPLEMENTATION

Table of Contents

Table of Contents

TUESDAY AM

ORAL SESSION O1
LEARNING AND GENERALIZATION

8:30 O1.1 **BIRDSONG LEARNING**

MARK KONISHI, Division of Biology, California Institute of Technology

Invited talk.

9:10 O1.2 **COMPARING GENERALIZATION BY HUMANS AND ADAPTIVE NETWORKS**

M. PAVEL, MARK A. GLUCK, VAN HENKLE, Department of Psychology, Stanford University

Generalization of a pattern categorization task was investigated in a simple, deterministic, inductive learning task. Each of eight patterns in a training set was specified in terms of four binary features. After subjects learned to categorize these patterns in a supervised learning paradigm, they were asked to generalize their knowledge by categorizing novel patterns. We analyzed both the details of the learning process as well as subjects' generalizations to novel patterns. Certain patterns in the training set were consistently found to be more difficult to learn than others. The subsequent generalizations made by subjects indicate that in spite of important individual differences subjects showed systematic similarities in how they generalized to novel situations. The generalization performance of subjects was compared to those that could possibly be generated by a two-layer adaptive network. A comparison of network and human generalizations indicates that using a minimal network architecture is not alone a sufficient constraint to guarantee that a network will generalize the way humans do.

9:40 O1.3 **AN OPTIMALITY PRINCIPLE FOR UNSUPERVISED LEARNING**

T. SANGER, Massachusetts Institute of Technology AI Laboratory

We present a general optimality criterion for unsupervised learning which can be used to design training algorithms. This criterion leads to the "Principle of Maximum Variance" which describes a method for choosing hidden layers in a multilayer network. We prove that this method is optimal, and in certain cases corresponds to the Karhunen-Loeve transform. We derive a new learning algorithm and we give an example of its use for a computer vision system. The algorithm finds significant local "features" in real images and can perform texture segmentation. Our results apply to both linear and nonlinear nets, and provide a rigorous mathematical basis for the study of unsupervised learning in feedforward neural networks.

10:10 **BREAK**

10:30 O1.4 LEARNING BY EXAMPLE WITH HINTS

YASER S. ABU-MOSTAFA, Departments of Electrical Engineering and Computer Science, California Institute of Technology

Learning by example is the process of mechanically producing an (exact or approximate) implementation of a function based merely on a (large) number of instances of the function. Recently, there have been a number of results that show learning by example to be NP-complete, hence probably intractable. Experience tells us that the learning process is drastically simplified if we take advantage of the "hints" we know about the function, instead of just using examples blindly. We address the formalization of what hints are and how they may reduce the complexity of learning by example.

11:00 O1.5 ASSOCIATIVE LEARNING VIA INHIBITORY SEARCH

DAVID H. ACKLEY, Cognitive Science Research Group, Bell Communications Research

ALVIS is a reinforcement-based connectionist architecture that learns associative maps in continuous multidimensional environments. . The discovered locations of positive and negative reinforcements are recorded in "do be" and "don't be" subnetworks, respectively. The outputs of the subnetworks relevant to the current goal are combined and compared with the current location to produce an error vector. This vector is backpropagated through a motor-perceptual mapping network to produce an action vector that leads the system towards do-be locations and away from don't-be locations. ALVIS is demonstrated with a simulated robot posed a target-seeking task.

11:30 O1.6 SPEEDY ALTERNATIVES TO BACK PROPAGATION

JOHN MOODY, CHRIS DARKEN, Computer Science Department, Yale University

We propose two neurally-inspired learning algorithms which offer much greater speed than Back Propagation. These algorithms are "Self-Organized Learning With Receptive Fields" and a multi-resolution, interpolating variant of the Cerebellar Model Articulation Controller (CMAC). Both algorithms share three critical features in common: they have only one layer of internal units, they utilize a self-organized representation of the input space on the internal layer, and their representation of the input space is localized or only slightly distributed. Furthermore, the CMAC learning rule requires modification of only the output weights. These features result in increased simulation speed. In detailed comparisons to Back Propagation for the problem of predicting Chaotic Time Series, these new algorithms learn as much as *one thousand times faster* than a very fast implementation of Back Propagation (conjugate gradient) while achieving comparable prediction capability on test data. Back Propagation, however, achieves its performance with a smaller set of training data. These algorithms are likely to provide similar speed increases in other problem domains. The self-organizing receptive field model is in principle implementable as an analog dynamical system. The CMAC can be conveniently implemented purely digitally or as a hybrid digital/analog system.

TUESDAY PM

POSTER SESSION P1A
LEARNING AND GENERALIZATION

12:00 **POSTER PREVIEW 1**

P1.1 EFFICIENT PARALLEL LEARNING ALGORITHMS FOR NEURAL NETWORKS

ALAN KRAMER, ALBERTO SANGIOVANNI-VINCENTELLI, Department of Electrical Engineering and Computer Science, University of California, Berkeley

We are interested in parallel algorithms for quickly finding local minima in the weightspace of feedforward neural-net learning problems. Backpropagation is unsuitable for our needs because of its bad convergence properties. We have implemented a partial conjugate-gradient algorithm based on the Polak-Ribiere rule and curve fitting techniques. This algorithm has good convergence properties and in practice we find that it always outperfoms backprop in terms of number of training set sweeps to convergence. Because our algorithm has small storage requirements it is well suited for parallel implementation on the Connection Machine.

P1.2 PROPERTIES OF A HYBRID NEURAL NETWORK-CLASSIFIER SYSTEM

LAWRENCE DAVIS, Bolt Beranek and Newman Laboratories, Cambridge, MA

A machine learning system is described, together with procedures for translating some representative neural networks and classifier systems into it. Procedures for translating some representative learning mechanisms of neural networks and classifier systems into the hybrid system are also given. The paper shows how learning procedures such as genetic operators and Hebbian reinforcement thought applicable only to one or the other sort of learning system may be cross-applied in the hybrid representation. The paper concludes with a discussion of interesting consequences of these results.

P1.3 SELF ORGANIZING NEURAL NETWORKS FOR THE IDENTIFICATION PROBLEM

M.F. TENORIO, WEI-TSIH LEE, School of Electrical Engineering, Purdue University

Identification of the system model plays an important role in various engineering fields, including control, computer vision and speech, and adaptive filtering. In this paper, we address the identification of nonparametric system models.

The Group Method Data Handling (GMDH) algorithm was conceived by Ivakhnenko in 1969. This algorithm embodies the idea of self organizing structures based on the Least Mean Square Error. The structure is generated by adding a perception-like layer, composed of two-input neurons which have quadratic transfer functions. The GMDH algorithm using a heuristic pruning criteria generates only feedforward suboptimal structures.

In order to identify optimal structures in the sense of complexity, we propose a new and more rigorous self organizing algorithm. From Information Theory, the algorithm uses the Minimum Descriptive Length criteria to guide a stochastic search in the function space, based on a modified simulated annealing.

When compared with previously known algorithms, this method allows for more general structures to be identified, and seems to choose the one that is optimal. The results of a complex polynomial system identification will be shown and discussed.

P1.4 COMPARISON OF MULTILAYER NETWORKS AND DATA ANALYSIS

P. GALLINARI, S. THIRIA*, F. FOGELMAN SOULIE, Laboratoire d'Intelligence Artificielle, Universite de Paris (*also at Conservatoire National des Arts et Metiers)

This paper will show how classical tools of Data Analysis can be compared with multi Layer networks trained with the Gradient Back Propagation algorithm.

We will also present methods which allow to use these tools to improve performances of the networks by providing adequate pre-processing of the data and indications on the appropriate number of hidden units.

P1.5 NEURAL NETWORKS AND PRINCIPAL COMPONENT ANALYSIS: LEARNING FROM EXAMPLES WITHOUT LOCAL MINIMA

PIERRE BALDI, KURT HORNIK**, Department of Mathematics, University of California, San Diego (**permanently at Technische Universitat Wien, Vienna)

We consider the problem of learning from examples in layerd linear-feed forward neural networks using optimization methods, such as back propagation, with respect to the usual quadratic error function E of the connection weights. Our main result is a complete description of the landscape attached to E in terms of principal component analysis. We show that E has a unique minimum corresponding to the projection onto the subspace generated by the first principal vectors of a covariance matrix associated with the training patterns. All the additional critical points of E are saddle points (corresponding to projections onto subspaces generated by higher order vectors). The auto-associative case is examined in detail. Extensions and implications for the learning algorithms are discussed.

P1.6 LEARNING BY CHOICE OF INTERNAL REPRESENTATIONS

TAL GROSSMAN, RONNY MEIR***, EYTAN DOMANY, Weizmann Institute of Science (***currently at Division of Chemistry, California Institute of Technology)

We introduce a learning algorithm for three-layer feedforward neural networks (two-layer perceptrons) composed of binary linear threshold elements. Whereas existing algorithms reduce the learning process to minimizing a cost function over the *weights*, our method treats the *internal representations* as the fundamental entities to be determined. Once a correct set of interna. representations is arrived at, the weights are found by the local and biologically plausible Perceptron Learning Rule (PLR). We tested our learning algorithm on three problems: adjacency, symmetry and parity.

P1.7 WHAT SIZE NET GIVES VALID GENERALIZATION?

ERIC B. BAUM, Jet Propulsion Laboratory, California Institute of Technology; DAVID HAUSSLER, Department of Computer and Information Sciences, University of California, Santa Cruz

We consider loading a training database onto a fixed neural net by back propagation or other learning methods, and address the question of when valid generalization can be expected. We assume only that we are trying to learn some fixed, unknown concept which classifies any example as positive or negative, and that training examples and future test examples are drawn independently at random (as in Valiant's learning protocol) from some fixed, unknown, arbitrary probability distribution. Under these assumptions we show how general learning results derived using the combinatorial notion of the "Vapnik-Chervonenkis" (VC) dimension (related to Cover's notion of "capacity") can be applied the problem of generalization in neural nets. In particular, using a recent calculation of the VC dimension of feedforward neural nets, we give tight bounds on the size net one should attempt to load a given training database of *m* examples on, if one wishes valid generalization to future examples.

P1.8 MEAN FIELD ANNEALING AND NEURAL NETWORKS

B. BILBRO, T.K. MILLER, W. SNYDER, D. VAN DEN BOUT, M. WHITE, Department of Electrical and Computer Engineering, North Carolina State University, Raleigh; R. MANN, Engineering Physics and Mathematics Division, Oak Ridge National Laboratory

Nearly optimal solutions to many combinatorial problems can be found using *simulated annealing* (SA). This paper uses *mean field theory* to replace the discrete degrees of freedom manipulated in simulated annealing with their continuous averages. The convergence of this *mean field annealing* (MFA) technique is 1-2 orders of magnitude faster than that of simulated annealing yet causes no degradation in the quality of the final solutions. The performance of MFA is demonstrated upon several example problems: graph partitioning, Boltzmann neural network convergence, and image restoration. A linkage is established between MFA and Hopfield neural networks which has important ramifications in the analysis and control of such networks.

P1.9 CONNECTIONIST LEARNING OF EXPERT PREFERENCES BY COMPARISON TRAINING

GERALD TESAURO, Center for Complex Systems Research, University of Illinois at Urbana-Champaign

A new training paradigm, called the "comparison paradigm," is introduced for tasks in which a network must learn to choose a preferred pattern from a set of *n* alternatives, based on examples of human expert preferences. In this paradigm, the input to the network consists of two of the *n* alternatives, and the trained output is the expert's judgement of which pattern is better. This paradigm is applied to the learning of backgammon, a difficult board game in which the expert selects a move from a set of legal moves. With comparison training, much higher levels of performance can be achieved, with networks that are much smaller, and with coding schemes that are much simpler and easier to understand. Furthermore, it is possible to set up the network so that it always produces consistent rank-orderings.

P1.10 DYNAMIC HYPOTHESIS FORMATION IN CONNECTIONIST NETWORKS

MICHAEL C. MOZER, Departments of Psychology and Computer Science, University of Toronto

This paper proposes a way of using the knowledge in a network to determine the functionality of individual units and connections. The basic idea is a bootstrapping approach: Take the network in its current state after some amount of training; use back propagation to compute the influence that particular units have on the output state; suppress the least salient units and continue training. This technique can be used to improve learning performance when the input contains irrelevant or redundant information, improve generalization by eliminating noise, and decrease the number of weight parameters in the network.

P1.11 THE BOLTZMANN PERCEPTRON: A MULTI-LAYERED FEED-FORWARD NETWORK EQUIVALENT TO THE BOLTZMANN MACHINE

EYAL YAIR, ALLEN GERSHO, Center for Information Processing Research, Department of Electrical and Computer Engineering, University of California, Santa Barbara

A deterministic, feed-forward networ, called the Boltzmann Perceptron, is introduced which has some of the characteristics of a multi-layer perceptron and is functionally equivalent to the Boltzmann machine for fuzzy pattern classification. A learning algorithm for this classifier is described. The

classifier performance and the learning algorithm will be demonstrated for solving a detection problem with Gaussian sources.

P1.12 ADAPTIVE NEURAL-NET PREPROCESSING FOR SIGNAL DETECTION IN NON-GAUSSIAN NOISE

PAUL E. BECKMAN, RICHARD P. LIPPMANN, Massachusetts Institute of Technology Lincoln Laboratory

A nonlinearity is required before matched filtering in minimum error receivers when additive noise is present which is impulsive and highly non-Gaussian. Experiments were performed to determine whether the correct clipping nonlinearity could be provided by a single-input single-output multi-layer perceptron trained with back propagation. It was found that multi-layer perceptrons with different numbers of layers and hidden nodes could be trained to provide the types of nonlinearities required with fewer than 5,000 presentations of noiseless and corrupted waveform samples. A trained network used as a front end for a linear matched filter detector greatly reduced the probability of error. In one representative condition the signal detection error rate dropped from 26% with a linear front-end to 4% with a trained net.

P1.13 TRAINING MULTILAYER PERCEPTRONS WITH THE EXTENDED KALMAN ALGORITHM

SHARAD SINGHAL, LANCE WU, Bell Communications Research, Morristown, NJ

Multilayer perceptrons are usually trained using the back-propagation algorithm described by Rumelhart et al. In this algorithm weight updates are made based on the gradient computed from only the current inputs and outputs; gradient information from previous data is ignored. Thus many weight changes are inconsistent and convergence is slow. In complex problems, thousands of iterations may be required for convergence.

In this paper, we apply the extended Kalman algorithm to multilayer perceptrons. Although it is computationally complex, this algorithm updates weights consistent with all previously seen data and usually converges in a few iterations. We describe the algorithm and compare it with back-propagation using several examples.

P1.14 GEMINI: GRADIENT ESTIMATION THROUGH MATRIX INVERSION AFTER NOISE INJECTION

Y. LECUN, C.C. GALLAND, G.E. HINTON, Computer Science Department and Physics Department, University of Toronto

Back-Propagation is more efficient, but less neurally plausible, than reinforcement learning that correlates random perturbations with changes in reinforcement. GEMINI is a hybrid procedure, readily implementable in hardware, which provides a biologically plausible model of gradient-descent learning in multilayer networks while approaching the efficiency of BP type procedures.

GEMINI injects noise only at the first hidden layer and measures the resultant effect on the output error. A linear network associated with each hidden layer iteratively inverts the matrix which relates the noise to the error change, thereby obtaining the error-derivatives. No back-propagation is involved, allowing unknown non-linearities in the system.

P1.15 ANALYSIS OF RECURRENT BACKPROPAGATION

PATRICE Y. SIMARD, MARY B. OTTAWAY, DANA H. BALLARD, Department of Computer Science, University of Rochester

This paper attempts a systematic analysis of the recurrent backpropagation (RBP) algorithm. We first show that there is a potential problem in that RBP always has unstable fixed points. We show by experiment and eigenvalue analysis that this is not the case. Next we examine the advantages of RBP over the standard backpropagation algorithm. RBP is shown to build stable fixed points corresponding to the input patterns. This makes it an appropriate tool for content addressable memory. Finally, we show that the introduction of a non-local search technique such as simulated annealing has a dramatic effect of a network's ability to learn patterns.

P1.16 SCALING AND GENERALIZATION IN NEURAL NETWORKS: A CASE STUDY

SUBUTAI AHMAD, GERALD TESAURO, Center for Complex Systems Research, University of Illinois at Urbana-Champaign

The issues of scaling and generalization are studied in the context of the majority function. We find that the failure rate, the fraction of misclassified test instances, falls off exponentially with the training set size. The number of training patterns required to achieve a fixed performance level increases linearly with the number of input units. It is shown that a boost in the performance level can be obtained by a simple change in the input representation. It is also shown that the most useful training examples are the ones closest to the separating surface.

P1.17 DOES THE NEURON "LEARN" LIKE THE SYNAPSE?

RAOUL TAWEL, Jet Propulsion Laboratory, California Institute of Technology

We describe an improved learning paradigm that promises to offer a significant reduction in computation time during the supervised learning phase. It is based on extending the role that the neuron plays in artificial neural systems. Prior work has regarded the neuron as a strictly passive non-linear processing element, and the synapse on the other hand as the primary source of information processing. In this work, the role of the neuron is extended and provides a secondary source of information processing. This is achieved by treating both the neuronal and synaptic parameters on an equal basis. The temperature (i.e. gain) of the sigmoid function is an example of such a parameter. In much the same way that the synaptic interconnection weights W_{ij}^{n} require optimization to reflect the knowledge contained within the training set, so are the temperature terms T_i^n. The indices i and n are used to refer to the temperature of the i^{th} neuron on the n^{th} layer of the network. Clearly, the method does not explicitly optimize a global temperature for the network, but allows each neuron to possess and update its own characteristic local temperature. This algorithm has been applied to logic type of problems, such as the XOR or parity problem, and significantly decreases the learning time on the posed problems. For example, in the XOR problem, the training time was decreased by over three orders of magnitude.

P1.18 EXPERIMENTS ON NETWORK LEARNING BY EXHAUSTIVE SEARCH

D.B. SCHWARTZ, J.S. DENKER, S.A. SOLLA, AT&T Bell Laboratories, Holmdel, NJ

We have performed experiments in which learning is explicitly formulated as a global search through the set of possible networks. We applied this to a problem that has also been extensively explored by conventional local iterative improvement techniques (e.g., back propagation). We have measured the error rate and the final entropy (S_m) of the network-ensemble after training with m examples, and find that they agree qualitatively with predictions of our simple theory.

P1.19 SOME COMPARISONS OF CONSTRAINTS FOR MINIMAL NETWORK CONSTRUCTION WITH BACKPROPAGATION

STEPHEN JOSE HANSON, Bell Communications Research, Morristown, NJ; LORIEN Y. PRATT, Rutgers University

Rumelhart has proposed a method for choosing minimal representations during learning in Backpropagation networks. This approach can be used to (a) dynamically select the number of hidden units, (b) construct a representation that is appropriate for the problem and (c) thus improve the generalization ability of Backpropagation networks.

The method Rumelhart suggests involves adding penalty terms to the usual error function. These terms will in effect cause some weights to decay sooner than others, essentially disconnecting parts of the network from one another. Various terms which are included in the objective function can be seen as biasing the search process to consider only representations of a certain type--those that minimize both the error and the penalty terms. Consequently the nature of the penalty terms are critical for choosing one representation over another and achieving the previously stated goals.

In this paper we introduce Rumelhart's *minimal networks* idea and compare several possible constraints on the weight search space. These constraints are compared in both simple counting problems and a real world speech recognition problem. In general, the constrained search does seem to minimize the number of hidden units required with an expected increase in local minima.

P1.20 IMPLEMENTING THE PRINCIPLE OF MAXIMUM INFORMATION PRESERVATION: LOCAL ALGORITHMS FOR BIOLOGICAL AND SYNTHETIC NETWORKS

RALPH LINSKER, IBM T.J. Watson Research Center, Yorktown Heights, NY

The principle of maximum information preservation has been proposed [R. Linsker, *Computer* 21 (3) 105-117 (March 1988)] as a *possible organizing principle for multilayerd perceptual networks*. Each resulting processing stage has the property that its output values *enable one to discriminate optimally* (in an information-theoretic sense) among the input patterns presented to it. I describe local algorithms for implementing this principle in certain types of nonlinear networks and adaptive filter banks. The resulting feature maps are discussed for input ensembles of interest for biological and synthetic network development. New results for feature map "magnification factors" are also obtained, and are consistent with biological expectations.

P1.21 BIOLOGICAL IMPLICATIONS OF A PULSE-CODED REFORMULATION OF KLOPF'S DIFFERENTIAL-HEBBIAN LEARNING ALGORITHM

MARK A. GLUCK, DAVID PARKER, ERIC REIFSNIDER, Stanford University

We present a pulse-coded reformulation of Klopf's (1987) Differential-Hebbian learning model. The time derivative of pulse coded information can be calculated without using any unstable differencing methods. Thus, learning algorithms such as Klopf's, which depend on computing derivatives of activations, are more easily and stably implemented in a pulse-coded system. Furthermore, through the use of discrete pulses as the inputs and outputs of the model, instead of levels of activation, the pulse-coded Differential-Hebbian model will more closely simulate the physical processes occurring in a single neuron. This allows us to explore possible further parallels between the model and the biological substrates underlying classical conditioning (see, e.g., Gluck & Thompson, 1987; Donegan, Gluck & Thompson, in press). From an engineering perspective, it also suggests possible designs for the implementation of simple, stable, real-time adaptive signal-processing systems.

TUESDAY PM

POSTER SESSION P1B
APPLICATIONS

P1.22 COMPARISON OF TWO LP PARAMETRIC REPRESENTATIONS IN A NEURAL NETWORK-BASED SPEECH RECOGNIZER

K.K. PALIWAL, Computer Systems and Communications Group, Tata Institute of Fundamental Research, Bombay

Although the different linear prediction (LP) parametric representations provide equivalent information about the short-time spectral envelope of speech, these representations are known to show differences in their speech recognition performance when used with conventional linear pattern classifiers. Recently, an error back-propagation algorithm has been reported in the literature for training the artificial neural networks and it has been shown that the multi-layer perceptron (MLP) classifiers which are nonlinear in nature can provide arbitrarily shaped decision surfaces in the multidimensional pattern space. The aim of the present paper is to see whether the different LP parametric representations show differences in their speech recognition performance for these nonlinear MLP classifiers, too. For this, the 2-layer, the 3-layer and the 4-layer perceptron classifiers are studied here for the following two LP parametric representations: 1) the LP coefficient representation and 2) the cepstral coefficient representation. The results for the conventional linear pattern classifiers are also provided here for the sake of completeness. It is shown that like the conventional pattern classifiers the MLP classifiers also result in better recognition performance for the cepstral coefficient representation than for the LP coefficient representation.

P1.23 NONLINEAR DYNAMICAL MODELING OF SPEECH USING NEURAL NETWORKS

NAFTALI TISHBY, AT&T Bell Laboratories, Murray Hill, NJ

Natural speech is shown to behave as an output of a low dimensional nonlinear dynamical system. The correlation dimension of the attractor of the speech signal is measured to be between 2-5 for voiced speech and 4-9 for unvoiced speech sound. By training a multilayered network as a nonlinear predictor, a dynamical system was created, which generated speech like signals, even without any excitation.

P1.24 USE OF MULTI-LAYERED NETWORKS FOR CODING SPEECH WITH PHONETIC FEATURES

YOSHUA BENGIO, RANATO DE MORI, School of Computer Science, McGill University

A new method is proposed for coding speech based on spectral samples and properties extracted using operators acting as windows analysing the data with variable time and frequency resolution, executed when certain preconditions are found in the data and feeding the input layer of several multi-layered neural networks. The error back-propagation algorithm was used to train the neural networks. In an experiment with the E-set (B,C,D,E,G,K,P,V,3) an overall error rate of 9.5% was obtained. In an experiment with transitions in the context of /a/, /ae/, /o/, and /u/ error rates of 3%, 4%, 0% and 0% respectively were obtained.

P1.25 SPEECH PRODUCTION USING NEURAL NETWORK WITH COOPERATIVE LEARNING MECHANISM

MITSUO KOMURA, AKIO TANAKA, International Institute for Advanced Study of Social Information Science, Fujitsu Limited, Shizuoka

We propose a new neural network model and its learning algorithm. The proposed neural network consists of four layers--input, hidden, output and final output layers. And the hidden and output layers are multiple. The proposed algorithm has following three features. (1) The singular points of BP (Back Propagation) algorithm are removed. (2) Using Spread Pattern Information (SI) learning algorithm proposed here, the network learns analog data accurately. (3) Using Cooperative Learning (CL) algorithm proposed here, it is possible to learn analog data stably and to obtain smooth outputs.

We have developed a speech production system. The system consists of a phonemic symbol production subsystem and an acoustic parameter production subsystem using the proposed neural network. We have succeeded in producing natural speech waves with high accuracy.

P1.26 TEMPORAL REPRESENTATIONS IN A CONNECTIONIST SPEECH SYSTEM

ERICH J. SMYTHE, Computer Science Department, Indiana University, Bloomington

SYREN is a connectionist model that uses temporal information from events in a speech signal for syllable recognition. The rates and directions of formant center transitions are identified, and an adaptive method associates transition events with each syllable. The system uses explicit temporal representations by converting temporal effects into spatial representations. SYREN uses implicit temporal representations in formant transition identification through node activation onset, decay, and transmission delays in sub-networks analogous to visual motion detector cells. SYREN recognizes 79% of six repetitions of 24 consonant-vowel syllables when tested on unseen data, and recognizes 100% of its training syllables.

P1.27 THEONET: A CONNECTIONIST EXPERT SYSTEM THAT ACTUALLY WORKS

RICHARD FOZZARD, LOUIS CECI, GARY BRADSHAW, Departments of Computer Science and Psychology, University of Colorado at Boulder

The Space Environment Laboratory in Boulder has collaborated with the University of Colorado to construct a small expert system for solar flare forecasting, called THEO. It performed as well as a skilled human forecaster. We have constructed *TheoNet*, a three-layer back-propagation connectionist network that learns to forecast flares as well as THEO does.

A study of the internal representations constructed by the network may give insights to the "microstructure" of reasoning processes in the human brain. *TheoNet's* success suggests that a connectionist network can perform the task of knowledge engineering automatically.

P1.28 AN INFORMATION THEORETIC APPROACH TO RULE-BASED CONNECTIONIST EXPERT SYSTEMS

RODNEY M. GOODMAN, JOHN W. MILLER, PADHRAIC SMYTH, California Institute of Technology

In this paper we present a new method for implementing fast expert systems using a neural network approach. The basis of our model is a new information theoretic approach to rule based induction and inferencing, and in this paper we show how such a model can be implemented on a connectionist architecture. We present an algorithm for automatically learning network weights which correspond to "rules" in our model, and show theoretically and via simulations how probabilistic inferencing is being performed by the network according to information theoretic principles.

P1.29 NEURAL TV IMAGE COMPRESSION USING HOPFIELD TYPE NETWORKS

M. NAILLON, J.B. THEETEN, G. NOCTURE, Laboratoires d'Electronique et de Physique Appliquee (Limeil Brevannes Cedex, France)

A self-organizing Hopfield network is currently being developed for Vector Quantization oriented toward television image compression, to optimize the codebook in case of a non-connex training set of vectors. The metastable states of the net are used as extra-codes in low image density regions. The self-organization, controlled by a distortion measure, is realized by learning adaptively, among the stable and the metastable states, the most relevant attractors for the coding task. The Minimal Overlap Learning (W. Krauth and M. Mezard, 1987) is shown to be optimal for making tractable the metastability.

P1.30 PERFORMANCE OF SYNTHETIC NEURAL NETWORK CLASSIFICATION OF NOISY RADAR SIGNALS

I. JOUNY, F.D. GARBER, ElectroScience Laboratory, Department of Electrical Engineering, Ohio State University

In this paper, several synthetic network models are used to classify radar signal measurements from five commercial aircraft. The performance of the classifiers is evaluated, by means of computer simulation studies, under a number of conditions concerning the noise and radar receiver models, and azimuth and elevation angle ambiguity. The results obtained using the synthetic neural network classifiers are compared with those obtained using an (optimal) maximum-likelihood classifier and a (minimum-distance) nearest-neighbor classifier. These results demonstrate the capability of synthetic network models to be trained (under noisy conditions) to classify noisy measurements of radar signals. It is also shown, through the results of classification studies, that classification systems based on synthetic network models can be designed to realize near-optimum performance, even in situations with measurement ambiguities and mismatch of noise power-levels for training and operation.

P1.31 THE NEURAL ANALOG DIFFUSION-ENHANCEMENT LAYER (NADEL) AND EARLY VISUAL PROCESSING

ALLEN M. WAXMAN, MICHAEL SIEBERT, Laboratory for Sensory Robotics, Boston University

We introduce a new class of neural network aimed at early visual processing; we call it a Neural Analog Diffusion-Enhancement Layer or NADEL. The network consists of two levels which are coupled through nonlinear feedback. The lower level is a two-dimensional diffusion map which accepts binary visual features as input (e.g., edges and points) and spreads activity over larger scales as a function of time. The upper layer is fed the activity from the diffusion layer and serves to locate local maxima in it. These local maxima are fed back to the diffusion layer using an on-center/off-surround shunting anatomy. The maxima are also available as output of the network. The network dynamics serves to cluster features on multiple scales and can be used to support a large variety of early visual processing tasks such as: extraction of corners and high curvature points, line end detection, filling gaps and completing contour boundaries, generating saccadic eye motion sequences, perceptual grouping on multiple scales, correspondence in long-range apparent motion, and building 2-D shape representations that are invariant to location, orientation and scale on the visual field. The NADEL is now being designed for implementation in Analog VLSI.

P1.32 A COOPERATIVE NETWORK FOR COLOR SEGMENTATION

A. HURLBERT, T. POGGIO, Center for Biological Information Processing and the Artificial Intelligence Laboratory, Massachusetts Institute of Technology

A crucial problem in the computation of color is to find changes in surface color irrespective of the illuminant. We have developed a cooperative network, similar to the stereo algorithm of Marr and

Poggio, that takes as input the ratio of image irradiances in two distinct spectral channels. The network gives satisfactory results on natural images, requiring a few iterations to assign constant colors to object surfaces. Discontinuities in color are localised with the help of edges in the brightness image that forms one of the inputs to the cooperative network. The algorithm may help to explain several phenomena associated with color constancy in animals.

P1.33 NEURAL NETWORK STAR PATTERN RECOGNITION FOR SPACECRAFT ATTITUDE DETERMINATION AND CONTROL

PHILLIP ALVELDA, MIGUEL A. SAN MARTIN, CHARLES E. BELL, JACOB BARHEN, Jet Propulsion Laboratory, California Institute of Technology

Some of the most complex spacecraft attitude determination and control tasks are ultimately governed by ground based systems and personnel. Conventional space-qualified systems face severe computational bottlenecks introduced by serial microprocessors operating on inherently parallel problems. New computer architectures based on the anatomy of the human brain seem to promise high speed and fault tolerant solutions to some of the inherent limitations of standard microprocessors. This paper will discuss the latest applications of artificial Neural Networks to the problem of star pattern recognition for spacecraft attitude determination.

P1.34 NEURAL NETWORKS THAT LEARN TO DISCRIMINATE SIMILAR KANJI CHARACTERS

YOSHIHIRO MORI, KAZUHIKO YOKOSAWA, ATR Auditory and Visual Perception Research Laboratories, Osaka

A neural network is applied to the problem of recognizing Kanji characters. With the back propagation network learning algorithm, a three-layered feed-forward network is trained to recognize similar handwritten Kanji characters. In addition, two new methods are utilized to make training effective. Recognition rates were 92.0% for testing samples and 99.5% for training samples. Through an analysis of connection weights, it became clear that trained networks could find the hierarchical structure of Kanji characters. This strategy of trained networks makes high recognition accuracy possible. Our results suggest that neural networks are very effective for Kanji character recognition.

P1.35 FURTHER EXPLORATIONS IN THE LEARNING OF VISUALLY-GUIDED REACHING: MAKING MURPHY SMARTER

BARTLETT W. MEL, Center for Complex Systems Research, University of Illinois at Urbana-Champaign

MURPHY is an unsupervised robot/camera learning system that has been applied to the problem of grabbing objects in the presence of obstacles. MURPHY's internal representations consist of several coarse-coded populations of simple units encoding both static and dynamic aspects of the sensory-motor environment. By moving its arm around in its visual field, MURPHY learns to relate motor commands to sensory consequences via simple one-layer weight modification among the various unit populations. Initially MURPHY grabs objects via heuristic search; recent enhancements allow MURPHY to minimize search and improve grabbing performance with practice. Under current investigation are a range of simple heuristics for obstacle avoidance that exploit the explicitly visual nature of MURPHY's principal internal representation.

P1.36 USING BACKPROPAGATION TO LEARN THE DYNAMICS OF A REAL ROBOT ARM

KEN GOLDBERG, BARAK PEARLMUTTER, Department of Computer Science, Carnegie Mellon University

The dynamics of a robot arm specify the torques necessary to achieve a desired trajectory. Application of these torques allows an arm to be controlled more accurately than with conventional feedback alone. Computing the dynamics is thus an active area of research in robotics. In this paper we apply a neural network to the dynamics problem and measure its performance on the CMU Direct Drive Arm II.

We use a *temporal window* of desired positions as input to a 3-layer backpropagation network. To test generalization, we identify a family of "pick and place" trajectories. After training on a random sample of five trajectories from this family (run on the physical arm) the network generalizes to members of the same family with root mean square errors of less than 4%. We find that generalization initially improves and then falls as window size is increased. We analyze the weights developed during the learning phase in terms of the velocity and acceleration filters used in conventional control theory.

Finally, we consider the network's ability to generalize to larger regions of the state space and report preliminary simulation results. Trained on a sample of 300 points chosen randomly from state space, a small backpropagation network can learn the training set with an RMS error of 1%, is able to generalize to the test trajectories with an RMS error of 0.7%, and is able to generalize to other points chosen randomly from phase space with an RMS error of 1.2%.

P1.37 BACKPROPAGATION AND ITS APPLICATION TO HANDWRITTEN SIGNATURE VERIFICATION

DOROTHY MIGHELL, JOSEPH GOODMAN, Stanford University

A pool of handwritten signatures is used to train a neural network for the task of deciding whether or not a given signature is a forgery. The network is a feedforward net, with a binary image as input. There is a hidden layer, with a single unit output layer. The weights are adjusted according to the backpropagation algorithm. The signatures are entered into a C software program through the use of a Datacopy Electronic Digitizing Camera. The binary signatures are normalized and centered. The performance is examined as a function of the training set and network structure. The best scores are on the order of 2% true signature rejection with 2-4% false signature acceptance.

TUESDAY PM

ORAL SESSION 02
APPLICATIONS

2:20 **O2.1 SPEECH RECOGNITION**

JOHN BRIDLE, Royal Radar Establishment, Malvern, U.K.

Invited talk.

3:00 **O2.2 APPLICATIONS OF ERROR BACK-PROPAGATION TO PHONETIC CLASSIFICATION**

HONG C. LEUNG, VICTOR W. ZUE, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology

This paper is concerned with the application of error back-propagation (BP) to pattern classification. Our investigation based on classification of the 16 spoken American vowels reveals that BP can integrate *heterogenous, numerical, and symbolic* sources of information. Depending on the amount of information provided, the network achieves performance ranging from 60% to 72%, which is comparable to the average agreement among human listeners. By using back propagation with a *weighted* mean square error, the rank-order statistics of the network can be improved. Training characteristics, self-organization into natural *articulatory* classes, rapid speaker adaptation, and direct comparisons with other classification techniques are also discussed.

3:30 **O2.3 MODULARITY IN NEURAL NETWORKS FOR SPEECH RECOGNITION**

A. WAIBEL, Department of Computer Science, Carnegie Mellon University

In this paper we show that neural networks for speech recognition can be constructed in a modular fashion by exploiting the hidden structure of previously trained phonetic subcategory networks. The performance of resulting larger phonetic nets was found to be as good as the performance of the subcomponent nets by themselves. This approach avoids the excessive learning times that would be necessary to train larger networks and allows for incremental learning (generally not easily possible in networks that inhibit incorrect output categories).

4:00 **BREAK**

4:20 **O2.4 NEURAL NETWORK RECOGNIZER FOR HAND-WRITTEN ZIP CODE DIGITS: REPRESENTATIONS, ALGORITHMS, AND HARDWARE**

J.S. DENKER, H.P. GRAF, L.D. JACKEL, R.E. HOWARD, W. HUBBARD, D. HENDERSON, W.R. GARDNER, AT&T Bell Laboratories, Holmdel, NJ; H.S. BAIRD, AT&T Bell Laboratories, Murray Hill, NJ; I. GUYON, ESPCI, Paris

A neural-network digit recognition system has been developed and used to classify handwritten zipcodes taken from actual envelopes. The system includes a VLSI chip for fast feature extraction. Numerous classifiers (neural and classical) were tested and compared. This process has exposed basic issues relevant to other categorization tasks.

4:50 **O2.5 ALVINN: AN AUTONOMOUS LAND VEHICLE IN A NEURAL NETWORK**

DEAN A. POMERLEAU, Computer Science Department, Carnegie Mellon University

ALVINN (Autonomous Land Vehicle In a Neural Network) is a back-propagation network designed for the navigational task of road following. Currently ALVINN is designed to process images from a video camera and a laser rangefinder, producing as output an estimate of the orientation of the road in the image and the direction the vehicle should travel to head towards the road center.

Training has been conducted using synthetic road images. Tests using novel synthetic roads and a limited number of real road sequences indicate the network should accurately follow actual roads. Currently we are implementing ALVINN on the NAVLAB vehicle at CMU to determine the performance of the network under field conditions. In order to increase road following accuracy we are also exploring various network architectures, including networks with feedback from one image to the next.

5:20 **O2.6 NEURAL NET RECEIVERS IN SPREAD-SPECTRUM MULTIPLE-ACCESS COMMUNICATION SYSTEMS**

BERND-PETER PARIS, GEOFFREY ORSAK, MAHESH K. VARANASI, BEHNAAM AAZHANG, Department of Electrical and Computer Engineering, Rice University

The application of neural networks to the demodulation of direct sequence spread-spectrum signals in a multiple-access environment is considered. The use of neural net receivers in this environment is motivated by the fact that the optimum receiver is too complex to be of practical use. The optimum receiver is used to benchmark the performance of the neural net receiver; in particular, it is proven to be instrumental in identifying the way decisions are made by the neural network. It is shown that the convergence of the back-propagation algorithm can be accelerated substantially by proper selection of the initial weights. Furthermore, the method of Importance Sampling is introduced to reduce the number of simulations necessary to evaluate the performance of neural nets. In all examples considered the proposed neural net receiver significantly outperforms the conventional matched filter receiver.

6:00 **BEER AND CHIPS**

8:00 **POSTER SESSION 1**

WEDNESDAY AM

ORAL SESSION 03
NEUROBIOLOGY

8:30 **O3.1 CRICKET WIND DETECTION**

JOHN MILLER, Department of Zoology, University of California, Berkeley

Invited talk.

9:10 **O3.2 A PASSIVE, SHARED ELEMENT ANALOG ELECTRONIC COCHLEA**

D. FELD, J. EISENBERG, E.R. LEWIS, Department of Electrical Engineering and Computer Science, University of California, Berkeley

We have simulated an electrical cochlea, which models the micromechanics of the human ear. In this respect it differs from other recent cochlear models that have been proposed. In our model we observe extraordinarily sharp high frequency rolloffs and linear phase, characteristics measured in the mammalian cochlea. We also observe corner frequencies spanning nearly seven octaves in the normal range of human audition. By basing our model on physiological structure, we can obtain a better understanding of the underlying mechanisms in the auditory system, leading to a more complete characterization of the parallel processing performed by front-end neural networks.

9:40 **O3.3 NEURONAL MAPS FOR SENSORY-MOTOR CONTROL IN THE BARN OWL**

C.D. SPENCE, J.C. PEARSON, J.J. GELFAND, R.M. PETERSON, David Sarnoff Research Center, Princeton, NJ; W.E. SULLIVAN, Department of Biology, Princeton University

The Barn Owl has fused visual/auditory/motor representations of space in its midbrain which are used to orient the head so that visual or auditory stimuli are centered in the visual field of view. We present models and computer simulations of these structures which address various problems, including the construction of a map of space from auditory sensory information, the adaptive fusion of information from different senses, and the problem of driving the motor system from these maps. We compare the results with biological data.

10:10 **BREAK**

10:30 **O3.4 SIMULATING CAT VISUAL CORTEX: CIRCUITRY UNDERLYING ORIENTATION SELECTIVITY**

U.J. WEHMEIER, D.C. VAN ESSEN, C. KOCH, Division of Biology , California Institute of Technology

Many models have been proposed to account for critical orientation and direction tuning in the visual system of mammals. We investigate a number of these strategies, in particular those invoking

intracortical inhibition, to test their agreement with known cortical anatomy and physiology. Our computer model of the early visual system in cat simulates the dynamics of neurons within a small (2° by 2°) patch of visual angle in the retina, its projection to LGN and its subsequent projection to layer IVc in cortical area 17. Extensions to the simulator also permit detailed modelling of individual cells in cortical layer IVc, as well as generation of receptive field contours of cortical cells.

11:00 **O3.5 MODEL OF OCULAR DOMINANCE COLUMN FORMATION: ANALYTICAL AND COMPUTATIONAL RESULTS**

K.D. MILLER, J.B. KELLER, M.P. STRYKER, Department of Physiology, University of California, San Francisco and Departments of Neuroscience and Mathematics, Stanford University

We have previously developed a simple mathematical model for formation of ocular dominance columns in mammalian visual cortex (Soc. Neur. Abs. 12:1373 (1986)). The model provides a common framework in which a variety of activity-dependent biological models can be studied.

Analytic and computational results together now reveal the following: if afferents within each eye are locally correlated in their firing, and are not anticorrelated within an arbor radius, monocular cells will robustly form and be organized by intra-cortical interactions into columns. Broader correlations within each eye, or anti-correlations between the eyes, create a more purely monocular cortex; positive correlation over an arbor radius yields an almost perfectly monocular cortex. The width of the columns, as determined by computing the power spectra of the columnar patterns, can be accurately predicted from the biological functions input to the model. The effects of monocular deprivation, modelled by reducing the activity within one eye, are accurately reproduced, and a critical period is seen. Most features of the model can be analytically understood through decomposition into eigenfunctions and linear stability analysis, allowing predictions of the results expected under a given plasticity model from measured biological parameters.

11:30 **O3.6 MODELING A CENTRAL PATTERN GENERATOR IN SOFTWARE AND HARDWARE: TRITONIA IN SEA MOSS**

S. RYCKEBUSCH, C. MEAD, J.M. BOWER, Computational Neural Systems Program, California Institute of Technology

We will present a model implemented in software and hardware (CMOS) of the central pattern generator that controls the swimming behavior of the marine molusc *Tritonia* This CPG is capable of generating different patterns of neuronal oscillations and resulting animal movements depending on the strength of the input that the animal receives from the sensory periphery. The CMOS implementations of a model of this system are capable of replicating this behavior. The CMOS circuit we have built is based on an analog equivalent neuron that has bursting properties similar to those found in the real neural network. We will describe and discuss the roles played by neuronal connections with different time constants in the activity of this neuron.

WEDNESDAY PM

POSTER SESSION P2A
NEUROBIOLOGY

12:00 **POSTER PREVIEW 2**

P2.1 STORAGE OF COVARIANCE BY THE SELECTIVE LONG-TERM POTENTIATION AND DEPRESSION OF SYNAPTIC STRENGTHS IN THE HIPPOCAMPUS

P.K. STANTON, J. JESTER, S. CHATTARJI, T.J. SEJNOWSKI, Department of Biophysics, Johns Hopkins University

Many network learning algorithms require mechanisms permitting both the long-term reduction as well as the enhancement of synapse strength. We are exploring the physiological conditions for the induction of long-term potentiation (LTP) and depression (LTD) of synaptic strengths in the hippocampus. The rhythmic bursting of a strong input is effective in producing LTP. We have found that a weak input which by itself does not cause any persistent change in synaptic strength can either increase in strength (associative LTP) or decrease in strength (associative LTD) depending on its phase of arrival within the rhythm of a strong input that produces LTP. Thus, information contained in the covariance of the weak and strong input can be stored (Sejnowski, T.J., J. Theo. *Biol.* 4: 203-211, 1976).

P2.2 A MATHEMATICAL MODEL OF THE OLFACTORY BULB

ZHAOPING LI, J.J. HOPFIELD, Division of Biology, California Institute of Technology

The olfactory bulb of mammals, the first processing center after the sensory cells in the olfactory pathway, is believed to aid in the discrimination of odors. A mathematical model based on the bulbar anatomy and electrophysiology has been constructed. Simulations produce a 35-60 Hz modulated activity which is coherent across the bulb, and mimics the observed field potentials. A linear analysis reveals the mechanism of oscillations and their patterns' dependence on odor inputs. Analysis and simulation show that the bulb, with appropriate inputs to its inhibitory cells from higher centers, can enhance or suppress the sensitivity to particular odors.

P2.3 A MODEL OF NEURAL CONTROL OF THE VESTIBULO-OCULAR REFLEX

M.G. PAULIN, S. LUDTKE, M. NELSON, J.M BOWER, Division of Biology, California Institute of Technology

During head movements there are compensatory eye movements which stabilize the eyes and improve visual acuity by reducing image movement across the retina. In the upper part of the bandwidth of natural head movements (2-10Hz in humans) eye stabilization is mainly due to the vestibulo-ocular reflex (VOR). Measurements of VOR dynamics indicate that the VOR is an optimal head velocity estimator which minimizes retinal image slip during head movements. We have constructed a neural network model based on the actual neural circuit topology underlying the VOR. The model generates the required dynamics for optimal VOR control in a stable manner using feedback loops between pools of neurons and transversal (delay line) filtering. We are extending the model to examine possible functional roles of cerebellar cortex in VOR control.

P2.4 ASSOCIATIVE LEARNING IN HERMISSENDA: A LUMPED PARAMETER COMPUTER MODEL OF NEUROPHYSIOLOGICAL PROCESSES

DANIEL L. ALKON, Laboratory of Molecular and Cellular Neurobiology, NINCDS, National Institutes of Health; FRANCIS QUEK, Environmental Research Institute of Michigan, Ann Arbor, MI; THOMAS P. VOGL, Environmental Research Institute of Michigan, Arlington, VA

Electrophysiological, biophysical, and biochemical measurements in individual neurons of the visual-vestibular pathways of numerous naive, conditioned, and sham-conditioned specimens of the marine mollusk, *Hermissenda crassicornis*, have demonstrated reproducible changes that are unique to associative learning as exemplified by classical conditioning. In order to provide corroborative evidence that these effects are necessary and sufficient to account for the observed learning, storage, and recall, a detailed lumped parameter computer model of the relevant neurons and their interconnections has been constructed. The model consists solely of neuronal features that can be justified explicitly on neurological and biophysical grounds, and the neurons are interconnected by previously mapped pathways. The computer model correctly reproduces the electrophysiological signals observed in nature before, during, and after inputs that mimic temporally associated and random light and rotation inputs. Particularly noteworthy is the necessity for incorporating into the model a number of features that fall into three broad categories: random neuronal firing, second order control mechanisms, and history (time) dependent neuronal responses. The potential contributions of such detailed computer models to both neurobiology and computer science are explored.

P2.5 RECONSTRUCTION OF THE ELECTRIC FIELDS OF THE WEAKLY ELECTRIC FISH GNATHONEMUS PETERSII GENERATED DURING EXPLORATORY ACTIVITY

B. RASNOW, Department of Physics, M.E. NELSON, J.M. BOWER, Department of Biology, C. ASSAD, Department of Electrical Engineering, California Institute of Technology

Active probing and exploration of the environment is characteristic of the behavior of most higher animals. In this paper we will present results relevant to motor control of movements which affect the positioning of sensory structures during active exploration. The weakly electric fish, *Gnathonemus petersii*, possesses an intriguing sensory-motor system in which electric fields are generated by an electric organ in the tail and small perturbations in the fields resulting from nearby objects in the surrounding environment are detected by electroreceptors distributed along the body surface. We will describe and present data from techniques which we have developed for recording body position and measuring electric fields during exploratory activity of these fish. This work represents a first step in quantifying the exploratory behavior of the fish and investigating possible computational strategies they use during active exploration of their environments.

P2.6 A MODEL FOR RESOLUTION ENHANCEMENT (HYPERACUITY) IN SENSORY REPRESENTATION

JUN ZHANG, Neurobiology Group, JOHN MILLER, Department of Zoology, University of California, Berkeley

Heiligenberg recently proposed a model to explain how sensory maps could enhance resolution through orderly arrangement of broadly tuned receptors. We have extended this model to a generalized case with arbitrary weighting schemes. We prove that for any polynomial weighting function $w(k)$, the response $f(x)$ is a polynomial function up to the same order. In particular, if $w(k)$ is a Hermitian polynomial, the resulting $f(x)$ will be the identical Hermitian function. For other spatially bounded weighting schemes, we prove the general result that $f(x)$ is proportional to $w(x)$, under some restrictions. We also addressed the problem of "edge-effect" introduced at the boundary of the receptor array. Finally, we investigated a real biological system (the cricket cercal sensory system) as an application of this model.

P2.7 CODING SCHEMES FOR MOTION COMPUTATION IN MAMMALIAN CORTEX

H. TAICHI WANG, BIMAL P. MATHUR, Science Center, Rockwell International, Thousand Oaks, CA; CHRISTOF KOCH, Division of Biology, California Institute of Technology

The representation and coding scheme chosen for a particular algorithm is crucial. In this paper, we report the implications of different coding schemes of the direction-selective representation for motion computation in the mammalian cortex, in terms of the performance and implementation of the resulting neural network models. Two coding schemes, the winner-take-all (WTA) coding and the population coding, are compared in detail. Our result show that the population coding scheme is likely to be the one used within cortex. While the shunting inhibition implementation of the WTA coding scheme is more attractive from the electronics implementation point of view.

P2.8 THEORY OF SELF-ORGANIZATION OF CORTICAL MAPS

SHIGERU TANAKA, Fundamental Research Laboratory of NEC Corporation, Kawasaki Kanagawa

We have shown mathematically that cortical maps in the primary sensory cortices can be made by using three hypotheses which do not conflict with physiological experimental results. Here, our main focus is on ocular dominance stripe formation in the primary visual cortex. Monte Carlo simulations on the segregation of ipsilateral and contralateral afferent terminals are carried out. Based on these, almost all the physiological experimental results concerning the ocular dominance stripes of cats and monkeys reared under normal or various abnormal conditions can be explained from a viewpoint of the critical phenomena.

P2.9 A BIFURCATION THEORY APPROACH TO THE PROGRAMMING OF PERIODIC ATTRACTORS IN NETWORKS MODELS OF OLFACTORY CORTEX

BILL BAIRD, Department of Biophysics, University of California, Berkeley

Analytic methods of bifurcation theory are used to design algorithms for de terming synaptic weights in various network models of olfactory bulb and prepyriform cortex. The result is memory storage of the kind of oscillating spatial patterns that appear in the bulb during inspiration and suffice to predict the pattern recognition behavior of rabbits in classical conditioning experiments. These attractors arise during simulated inspiration through a multiple Hopf bifurcation which acts as a critical "decision point" for their selection by the input pattern. Basin boundaries may also be programmed, and the location of secondary bifurcations which introduce new attractors can be controlled.

P2.10 NEURONAL CARTOGRAPHY: POPULATION CODING AND RESOLUTION ENHANCEMENT THROUGH ARRAYS OF BROADLY TUNED CELLS

PIERRE BALDI, Department of Mathematics; WALTER HEILIGENBERG, Neurobiology Unit, SIO, University of California, San Diego

We investigate population coding and resolution enhancement in sensori and motor maps. Starting from a few biological examples, we consider a simple model consisting of a one-dimensional array of evenly spaced cells with bell shaped turning curves. These cells provide inputs proportional to their degree of excitation as well as to their rank within the array so that the overall response can be taken to be of the form: $f(x) = \Sigma\, k \exp[-(x-k)^2/d]$. We show that as d is increased, f approaches a linear function in a very rapid and robust fashion and that, the wider the tuning curves, the more precise is the overall computation. We study the effect of different types of noise and boundary conditions on the model together with several of its extensions: "mexican hat" response curves, 2-D arrays, ... and show that its basic features are always preserved. We examine its potential engineering applications and biological plausibility: ontogeny, dynamic range, eye motor control, cochlea, ... and discuss its limitations.

P2.11 LEARNING THE SOLUTION TO THE APERTURE PROBLEM FOR PATTERN MOTION WITH A HEBB RULE

MARTIN I. SERENO, Division of Biology, California Institute of Technology

The primate visual system learns to recognize the true direction of pattern motion using local detectors only capable of detecting the component of motion perpendicular to the orientation of the moving edge. A multilayer feedforward network model similar to Linsker's model was presented with input patterns each consisting of randomly oriented contours moving in a particular direction. Input layer units have component direction and speed tuning curves similar to those recorded from neurons in primate visual area V1 that project to MT. The network is trained on many such patterns until most weights saturate. A proportion of the units in the second and higher layers solve the aperture problem (e.g., show the same direction-tuning curve peak to plaids as to gratings) resembling pattern-direction selective neurons in primate visual cortex, which first appear in area MT.

P2.12 A MODEL FOR NEURAL DIRECTIONAL SELECTIVITY THAT EXHIBITS ROBUST DIRECTION OF MOTION COMPUTATION

NORBERTO M. GRZYWACZ, FRANKLIN R. AMTHOR, Center for Biological Information Processing, Whitaker College, Cambridge, MA

Directionally selective retinal ganglion cells discriminate direction of visual motion relatively independently of speed (Amthor and Grzywacz, 1988a) and contrast. An asymmetric distribution of nonlinear inhibition around each point of the receptive field generates a directional selectivity that is computed multiple times in parallel over the field (Barlow and Levick, 1965). We propose a directional selectivity model based on our recent data on this inhibition's spatio-temporal and nonlinear properties. The main prediction of this model is the robust computation of visual motion direction. This robustness means that although a cell response depends on speed and contrast, the ratio of responses of cells having different preferred directions is independent. This suggests that the spatio-temporal properties of retinal directionally selective cells are particularly well adapted to motion computations.

P2.13 A LOW-POWER CMOS CIRCUIT WHICH EMULATES TEMPORAL ELECTRICAL PROPERTIES OF NEURONS

JACK MEADOR, CLINT COLE, Department of Electrical and Computer Engineering, Washington State University, Pullman, WA

This paper describes a CMOS artificial neuron. The circuit is directly derived from the voltage-gated channel model of neural membrane, has low power dissipation, and small layout geometry. The principal motivations behind this work include a desire for high performance, more accurate neuron emulation, and the need for higher density in practical neural network implementations.

P2.14 A GENERAL PURPOSE NEURAL NETWORK SIMULATOR FOR IMPLEMENTING REALISTIC MODELS OF NEURAL CIRCUITS

M.A. WILSON, U.S. BHALLA, J.D. UHLEY, J.M BOWER, Division of Biology, California Institute of Technology

To facilitate the design of detailed, realistic biologically-based models we have developed a graphically-oriented general purpose network simulator designed to support simulations ranging from detailed single cell models to large networks of simple or complex cells. Current models developed under this system include mammalian olfactory bulb and cortex, invertebrate central pattern generators, as well as more abstracted connectionist level simulations.

WEDNESDAY PM

POSTER SESSION P2B
STRUCTURED NETWORKS

P2.15 TRAINING A 3-NODE NEURAL NETWORK IS NP-COMPLETE

AVRIM BLUM, RONALD L. RIVEST, Laboratory for Computer Science, Massachusetts Institute of Technology

We consider a simple 2-layer, 3-node, *n*-input neural network whose nodes compute linear threshold functions of their inputs. We show that it is NP-Complete to decide whether there exist functions for the nodes of this network so that it will produce output consistent with a given set of *O(n)* training examples. We show NP-Completeness by reduction from Set-Splitting.

Our proof involves translating the learning problem into a geometrical setting. An equivalent statement of our result is that it is NP-Complete to decide whether two sets of boolean vectors in *n*-dimensional space can be linearly separated by two hyperplanes.

It is left as an open problem to extend our results to nodes with non-linear functions such as sigmoids.

P2.16 A MASSIVELY PARALLEL SELF-TUNING CONTEXT-FREE PARSER

EUGENE SANTOS, JR., Department of Computer Science, Brown University

The Parsing and Learning System (PALS) is a massively parallel self-tuning context-free parser. It is capable of parsing sentences of unbounded length mainly due to its parse-tree representation scheme. The system is capable of improving its parsing performance through the presentation of training examples.

P2.17 A BACK-PROPAGATION ALGORITHM WITH OPTIMAL USE OF HIDDEN UNITS

YVES CHAUVIN, Thomson CSF, Inc. and Stanford University

This paper presents a variation of the back-propagation algorithm that makes optimal use of hidden units by decreasing an "energy" term written as a function of the squared activations of these hidden units. The algorithm can (1) automatically find nearly optimal architectures necessary to solve known Boolean functions (2) facilitate the interpretation of the activation of the remaining hidden units (3) eliminate (0,0) local minimum while preserving the much faster convergence of the (-1,+1) logistic activation function and (4) automatically estimate the complexity of architectures appropriate for phonetic labeling problems.

P2.18 ANALYZING THE ENERGY LANDSCAPES OF DISTRIBUTED WINNER-TAKE-ALL NETWORKS

DAVID S. TOURETZKY, Computer Science Department, Carnegie Mellon University

When winner-take-all networks appear as components of larger connectionist systems, one must make compromises in setting their thresholds to ensure good overall system behavior. This proved to

be a significant problem when designing DCPS, Touretzky and Hinton's distributed connectionist production system. An analysis of the shape of the energy landscape explains why one solution eventually worked, and suggests an interesting alternative. The first approach, *rebiasing*, was employed in DCPS after the network had settled to reject choices in winner-take-all spaces that were not supported by adequate evidence. The second approach enables higher thresholds to be used by clipping the corners of the state-space hypercube to keep the model from turning all its units off during the annealing search.

2.19 DYNAMIC, NON-LOCAL ROLE BINDINGS AND INFERENCING IN A LOCALIST NETWORK FOR NATURAL LANGUAGE UNDERSTANDING

TRENT E. LANGE, MICHAEL G. DYER, Artificial Intelligence Laboratory, Computer Science Department, University of California, Los Angeles

The inability of previous distributed and localist networks to robustly handle non-local role-bindings has limited their usage in higher-level natural language understanding systems. This paper introduces a means to handle the critical problem of non-local role-bindings in localist spreading-activation networks.

Every conceptual node in the network has associated with it an identification node broadcasting a constant, uniquely-identifying activation, called its signature. Dynamic role-bindings are represented with nodes whose activations match the signatures of the bound concepts. Most importantly, the model passes these signatures, as activation, across long paths of nodes to handle the non-local role-bindings necessary for inferencing. We claim that role-bindings can be plausibly represented with groups of pacemaker neurons encoding these signature activations.

Using these abilities, our localist network model is able to robustly represent schemata role-bindings and thus perform the inferencing, plan/goal analysis, schema instantiation, word-sense disambiguation, and dynamic re-interpretation portions of the natural language understanding process

P2.20 SPREADING ACTIVATION OVER DISTRIBUTED MICROFEATURES

JAMES HENDLER, Department of Computer Science, University of Maryland, College Park

In this paper we demonstrate that an activation spreading mechanism can be used to probe the internal representations built by a distributed connectionist learning algorithm. We demonstrate that a variant of marker-passing can be used to perform symbolic inferencing types of behavior, in the absence of asymbolic model, when activation is spread through the weight space learned by a back-propagation algorithm. These sorts of inferences, previously made only by traditional AI representations and structured connectionist networks, are necessary for providing distributed networks with an ability to do the "subsymbolic inferencing" necessary for cognitive modeling.

P2.21 SHORT-TERM MEMORY AS A METASTABLE STATE: A MODEL OF NEURAL OSCILLATOR FOR A UNIFIED SUBMODULE

A.B. KIRILLOV, G.N. BORISYUK, R.M. BORISYUK, Ye.I. KOVALENKO, V.I. KRYUKOV, V.I. MAKARENKO, V.A. CHULAEVSKY, Research Computer Center of the USSR Academy of Sciences, Pushchino, Moscow Region

A new model of a controlled neuron oscillator, proposed earlier for the interpretation of the neural activity in various parts of the central nervous system, may have important applications in engineering and in the theory of brain functions. The oscillator has a good stability of the oscillation period, its frequency is regulated linearly in a wide range and it can exhibit arbitrarily long oscillation periods without changing the time constants of its elements. The latter is achieved by using the critical slowdown in the dynamics arising in a network of nonformal excitatory neurons. By changing the parameters of the oscillator one can obtain various functional modes which are necessary to develop a model of higher brain function.

P2.22 STATISTICAL PREDICTION WITH KANERVA'S SPARSE DISTRIBUTED MEMORY

DAVID ROGERS, Research Institute for Advanced Computer Science, NASA Ames Research Center

A new viewpoint of the processing performed by Kanerva's sparse distributed memory (SDM) is presented. In conditions of near- or over-capacity, where the associative-memory behavior of the model breaks down, the processing performed by the model can be interpreted as that of a *statistical predictor.* Mathematical results are presented which serve as the framework for a new statistical viewpoint of the processing done by a SDM, and for which the standard formulation of SDM is a special case. This viewpoint suggests possible enhancements to the SDM model, including a procedure for improving the predictiveness of the system, based on Holland's work with "Genetic Algorithms," and a method for improving the capacity of SDM even when used as an associative memory.

P2.23 IMAGE RESTORATION BY MEAN FIELD ANNEALING

G.L. BILBRO, W.E. SNYDER, Department of Electrical and Computer Engineering, North Carolina State University, Raleigh

Minimization by *stochastic simulated annealing* (SSA) has been used successfully by a number of authors to minimize functions of many variables, even in the presence of local minima. In this paper, a new minimization strategy is formulated in which the Markov random process of SSA is replaced by a deterministic minimization step followed by annealing. Experiments have indicated speedups of 1-2 orders of magnitude using this new *mean field annealing* (MFA) over SSA implementations of the same problem.

An abbreviated derivation of the MFA strategy is presented. Then, a particular objective functions is presented, one which minimizes the noise in an image while still preserving edges. The objective function is cast as an MFA problem and solved. Experimental results are presented in which noisy images are restored with sufficient accuracy to allow good estimates of second derivatives. Favorable comparisons are made with techniques previously reported in the literature. Restorations of very coarsely sampled images (16x16) are also presented, in which the noise is removed without distorting the edges.

The application of MFA to image restoration may be implemented on a locally-connected neural net. Implementation issues are presented.

P2.24 AUTOMATIC LOCAL ANNEALING

JARED LEINBACH, Department of Psychology, Carnegie Mellon University

This research involves a method for finding global maxima in constrain satisfaction networks. It is an annealing process but, unlike the Boltzmann Machine, requires no annealing schedule. Units determine their temperature at each update based solely on information local to them, and thus *all* processing is done at the unit level. The method outperforms the Boltzmann machine in two fundamental ways: 1) Global maxima are found more quickly, and 2) the probability of having found a global maximum always approaches 1 as the number of cycles of processing increases (for the Boltzmann Machine the probability of having found a global maximum stops increasing, at some value less than 1, when the temperature reaches zero). Implementation of this method is also computationally trivial.

P2.25 NEURAL NETWORKS FOR MODEL MATCHING AND PERCEPTUAL ORGANIZATION

ERIC MJOLSNESS, P. ANANDAN, Department of Computer Science; GENE GINDI, Department of Electrical Engineering, Yale University

We introduce an optimization approach for solving problems in computer vision that involve multiple levels of abstraction. Specifically, our objective functions can include compositional hierarchies

involving object-part relationships and specialization hierarchies involving object-class relationships. The large class of vision problems that can be subsumed by this method includes traditional model matching, perceptual grouping, dense field computation (regularization), and even early feature detection which is often formulated as a simple filtering operation. Our approach involves casting a variety of vision problems as inexact graph matching problems, formulating graph matching in terms of constrained optimization, and using analog neural networks to perform the constrained optimization. We will show the application of this approach to shape recognition in a domain of stick-figures and to the perceptual grouping of line segments into long lines.

P2.26 ON THE K-WINNERS-TAKE-ALL FEEDBACK NETWORK AND APPLICATIONS

ERIC MAJANI, RUTH ERLANSON, YASER ABU-MOSTAFA, Jet Propulsion Laboratory, California Institute of Technology

We present a rigorous analysis of the k-Winners-Take-All Feedback Network. We show that the slope G of the sigmoid at the origin has to be above a value of at least (N - 1) for the network to function properly (N is the number of nodes). In the limit of an infinite slope, we show that the only stable states of the network are the vectors with k (+1)'*s* and (N - k) (-1)'*s*, and that the convergence towards the stable state occurs in a maximum likelihood fashion. Finally, we use these networks for the soft decision decoding of Simplex Codes as well as Associative Memories.

P2.27 AN ADAPTIVE NETWORK THAT LEARNS SEQUENCES OF TRANSITIONS

C.L. WINTER, Science Applications International Corp., Tucson, AZ

We describe an adaptive network (TIN-2) that learns the transition function of an arbitrary finite-state automaton from observations of its real-time behavior. During training it abstracts transition functions from noisy data, while in operation it produces sequences of transitions in response to variations in input. Memory dynamics are based on a modified version of Adaptive Resonance Theory. Individual F_2 nodes learn to recognize unique current state/next state associations and all external inputs which have evoked them. We give results from experiments in which TIN-2 learns to balance parentheses in simple algebraic expressions from example expressions.

P2.28 CONVERGENCE AND PATTERN-STABILIZATION IN THE BOLTZMANN MACHINE

MOSHE KAM, Department of Electrical and Computer Engineering, Drexel University; ROGER CHENG, Department of Electrical Engineering, Princeton University

The most common application of the Boltzmann Machine is in global optimization with multimodal objective functions through the employment of simulated annealing. When operating at a constant temperature, the machine could be used for unambiguous associative pattern retrieval, through exploitation of its ability to escape from local minima. Through a learning algorithm, a set of known codewords is installed in the network's state space as a set of local minima. An appropriate *proximity criterion* is used to associate any binary tuple that comes close enough to a stored codeword with this codeword, effectively creating regions of attraction around each taught binary pattern. Spurious local minima, which become non-interpretable "traps" in the asynchronous deterministic model are skipped, and their effect on information retrieval is demonstrated only in delaying the machine in the (usually shallow) spurious "valleys" in the energy landscape before moving towards a "legal" interpretable minimum.

We formulate the Hamming distance from a stored pattern of a dynamic Boltzmann machine as a birth-and-death Markov chain, and find limits on the error-correcting capabilities of the resulting content-addressable memory in terms of retrieval probabilities and retrieval time. Steady state partition of the memory is studied through the process' limit state probabilities. In passing, we examine the role of the incremental Hebbian rule as a learning scheme for the machine, and interpret is as a steepest-descent algorithm, maximizing pattern stabilization during training. The results apply

to the assessment of coding efficiency for representing information to-be-stored, and to quantifying learning algorithms and association rules for both the Boltzmann machine and the asynchronous net of binary threshold elements.

WEDNESDAY PM

POSTER SESSION P2C
IMPLEMENTATION

P2.29 MOS CHARGE STORAGE OF ADAPTIVE NETWORKS

R.E. HOWARD, D.B. SCHWARTZ, AT&T Bell Laboratories, Holmdel, NJ

We have developed fully analog adaptive network chips which store the weights as charge upon MOS capacitors. The weights are changed by moving charge between a pair of capacitors with a string of charge transfer transistors that mimic CCD's. The charge transfer mechanism provides a resolution of 8 bits plus sign and implements weight decay simply. This resolution can be held for at least 20 seconds at room temperature, allowing ample time for refresh and can be held indefinitely if the chips are cooled. A 2.5μ CMOS chip with 128 weights and separate test structures has been tested and testing has begun on a 1.25μ version with 1104 weights.

P2.30 A SELF-LEARNING NEURAL NETWORK

A. HARTSTEIN, R.H. KOCH, IBM T.J. Watson Research Center, Yorktown Heights, NY

We propose a new neural network structure that is compatible with silicon technology and has built in learning capability. This network has the feature that the learning parameter is embodied in the thresholds of MOSFET devices and is local in character. The network is shown to be capable of learning by example as well as exhibiting the desirable features of the Hopfield type networks.

P2.31 AN ANALOG VLSI CHIP FOR CUBIC SPLINE SURFACE INTERPOLATION

JOHN G. HARRIS, Division of Computation and Neural Systems, California Institute of Technology

This paper describes an analog VLSI chip for smooth surface interpolation. An eight-node 1D network was designed in 3um CMOS [Mead 1988]. Subtract constraint devices and a resistor mesh are used to interpolate a dense surface from sparse depth constraints provided by a stereo module. The cubic spline interpolant used by this chip matches the results of psychophysics experiments with random dot stereograms.

P2.32 ANALOG IMPLEMENTATION OF SHUNTING NEURAL NETWORKS

BAHRAM NABET, ROBERT B. DARLING, ROBERT B. PINTER, Department of Electrical Engineering, University of Washington, Seattle

We propose an extremely compact, all analog and fully parallel implementation of a shunting cooperative-competitive recurrent neural network that is applicable to a wide variety of FET-based integration technologies. While the contrast enhancement, data compression, and adaptation to mean input intensity capabilities of the network are well suited for processing of sensory information or feature extraction for a content addressable memory (CAM) system, the network also admits a global Liapunov function and can thus achieve stable CAM storage itself. In addition, the model can readily function as a front-end processor to an analog adaptive resonance circuit.

P2.33 STABILITY OF ANALOG NEURAL NETWORKS WITH TIME DELAY

C.M. MARCUS, R.M. WESTERVELT, Division of Applied Sciences and Department of Physics, Harvard University

Analog neural networks designed to converge to fixed points can oscillate when time delay is present. This is an important consideration in building hardware networks where switching delay can be comparable to the relaxation time of the circuit. We consider stability in networks of saturable amplifiers (neurons) with delayed output. Our results are based on linear stability analysis about the fixed point where all neurons have maximum gain. We focus on symmetrically connected networks which are stable when the delay is zero, and show that above a critical value of delay an attractor for sustained oscillation appears. Our results can be formulated as a stability criterion that depends on the size and relaxation time of the network, the connection topology, and the delay and gain of the neurons. We apply the stability criterion to several connection topologies and show that the most unstable configuration is the all-inhibitory network and that Hebb rule networks are stable even for large delays. We also consider stability in random symmetric networks.

Results of the stability analysis agree well with numerical integration of the delay equations and experiments on a small (8 neuron) analog network that includes adjustable time delay based on charge coupled device circuitry.

P2.34 ANALOG SUBTHRESHOLD VLSI CIRCUIT FOR INTERPOLATING SPARSELY SAMPLED 2-D SURFACES USING RESISTIVE NETWORKS

JIN LUO, CHRISTOF KOCH, CARVER MEAD, California Institute of Technology

Interpolating and smoothing sparsely sampled and noisy surface data is a well-known problem in computer vision (Grimson, 1981). It can be shown to be equivalent to minimizing a quadratic variational functional. This functional maps onto very simple resistive networks, such that the steady state voltage distribution corresponds to the interpolated and smoothed surface (Koch, Marroquin and Yuille, 1986). We have implemented such a network using analog, subthreshold CMOS VLSI technology (Mead, 1988) and report here for the first time its full two-dimensional operation using real data.

P2.35 GENERAL PURPOSE NEURAL ANALOG COMPUTER

PAUL MUELLER, JAN VAN DER SPIEGEL, DAVID BLACKMAN, JOE DAO, CHRIS DONHAM, ROY FURMAN, DZU PU HSIEH, MARC LOINAZ, Departments of Biochemistry and Biophysics and Electrical Engineering, University of Pennsylvania

We have designed a neural analog computer and are in the process of fabricating its components. The machine is assembled from separate modules consisting of neuron arrays, variable gain synaptic arrays, and switchable axon arrays. The machine runs entirely in analog mode but all parameters (neuron thresholds and time constants, connections and synaptic weights are under digital control).

Each neuron has a limited number of inputs (128), and can connect to any other neuron but not every neuron can connect to every other neuron. Connections (via axons), neuron parameters (threshold, time constants) and synaptic gains (weights) are set from digital processors, each processor serving a section of neurons, axons and synapses.

Neuron arrays are arranged in rows and columns and are surrounded by synaptic and axon arrays. For determining synaptic weights (learning mode), outputs from neurons are multiplexed, A/D converted and stored in digital memory.

Learning algorithms or connection architectures are generated by a central digital computer that serves each section processor. Because of its modular design the machine can be expanded to any size.

P2.36 A SILICON BASED PHOTORECEPTOR SENSITIVE TO SMALL CHANGES IN LIGHT INTENSITY

C.A. MEAD, T. DELBRUCK, California Institute of Technology

We describe a silicon-based photoreceptor circuit that is sensitive to small changes in the incident light intensity. The idea for the circuit came from a suggestion by Frank Werblin that biological retinas may achieve great sensitivity to small changes in incident intensity by feeding back a filtered version of the output signal. A comparison between measurements of temporal contrast sensitivity for the circuit and for the human eye, measured psychophysically, are presented and it is shown that both obey Weber's law and that the contrast sensitivities are nearly the same when measured in units of incident intensity. We discuss how the circuit achieves this in terms of the small signal gain control.

P2.37 A DIGITAL REALISATION OF SELF-ORGANISING MAPS

M.J. JOHNSON, N.M. ALLINSON, K. MOON, Department of Electronics, University of York, England

A novel digital realization for a self-organising feature map is proposed. This is shown to be equivalent to the analogue form and has been used to create very large feature maps for image primitives. A 256x256 feature map of 32x32 weight elements was found to produce an adapted output map in under 50ms using a single processor running at four MIPS, and with a memory requirement of approximately two Mbytes.

P2.38 TRAINING OF A LIMITED-INTERCONNECT, SYNTHETIC NEURAL IC

M.R. WALKER, L.A. AKERS, Center for Solid-State Electronics Research, Arizona State University, Tempe

This paper reports on the development of a non-algorithmic training paradigm for a limited-interconnect, multi-layered perceptron-like network implemented using standard CMOS design rules. The network is isomorphic to fully-connected layered architectures, but satisfies the interconnection length and density constraints imposed by VLSI technology. The network is composed of 512 compact analog processing elements, each of which modulates inputs with analog synaptic transmittance values and then sums the post-synaptic signals on the gate of a CMOS double inverter. The training paradigm is a modified version of back-propagation which accommodates the binary-state processing elements and the limited range of synaptic weight values imposed by microelectronic constraints. Simulation results are presented which demonstrate the ability of this paradigm to produce a network which is fault tolerant and capable of generalization.

P2.39 ELECTRONIC RECEPTORS FOR TACTILE SENSING

ANDREAS G. ANDREOU, Department of Electrical and Computer Engineering, Johns Hopkins University

In this paper, we discuss electronic receptors for tactile sensing. These are based on magnetic field sensors both Hall-effect structures and magneto-transistors fabricated using standard CMOS technologies, and integrated with additional electronics to perform local processing. Integrated arrays of these receptors biased with a small permanent magnet, can sense the local distortion in the magnetic field due to paramagnetic objects near the surface of the chip. The sensitivity, spatial resolution and frequency response of different receptors fabricated through MOSIS will be discussed. The above performance criteria will be compared with the characteristics of different types of biological tactile receptors.

P2.40 OPTICAL EXPERIMENTS IN LEARNING, COOPERATION, AND COMPETITION WITH CONTINUOUS, DYNAMIC HOLOGRAPHIC MEDIA

JEFF L. ORREY, MIKE J. O'CALLAGHAN, PETER J. MARTIN, DIANA M. LININGER, DANA Z. ANDERSON, Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder

We present two classes of optical neural networks. In an electrooptic version we demonstrate delta rule learning, with synaptic weights stored and updated in a dynamic volume holographic medium. Updating consists of adjusting the diffraction efficiency of the hologram via a liquid crystal spatial light modulator and microcomputer. For an all optical nonlinear circuit with active gain and loss we discuss competitive and cooperative interactions between modes. We present experimental results illustrating mode dynamics, including bistability, hysteresis and relaxation oscillations.

WEDNESDAY PM

ORAL SESSION 04
STRUCTURED NETWORKS

2:20 04.1 SYMBOL PROCESSING IN THE BRAIN

GEOFFREY HINTON, Computer Science Department, University of Toronto

Invited talk.

3:00 O4.2 IMPLICATIONS OF RECURSIVE DISTRIBUTED REPRESENTATIONS

JORDAN POLLACK, New Mexico State University, Las Cruces

I will describe my recent results on the automatic development of fixed-width distributed representations of variable-sized recursive and sequential data structures: Recursive Auto-Associative Memory (RAAM), which implements Hinton's idea of reduced descriptions.

The first implication of this work is that certain types of AI-style data-structures can now be represented in fixed-width analog vectors. Simple inferences and transformations can be done quickly by the type of pattern associations that neural networks excel at, thus avoiding the combinatorial inefficiencies of variables, unification, or data-restructuring.

The second implication is that these representations must become self-similar in the limit. Once this door to chaos is opened, many interesting new questions about intelligence can (and will) be discussed.

3:30 O4.3 LEARNING SEQUENTIAL STRUCTURE IN SIMPLE RECURRENT NETWORKS

DAVID SERVAN-SCHREIBER, AXEL CLEEREMANS, JAMES L. McCLELLAND, Departments of Computer Science and Psychology, Carnegie Mellon University

This paper reports a study of learning in simple recurrent networks previously studied by Elman (1988). In these networks, the pattern of activation developed on a hidden layer at *t-1* and the event that occurred at *t-1* are used to predict the event that will occur at *t*. We trained the network on a set of letter strings of restricted length from a simple artificial grammar. After training, the network was able to predict possible successors of each letter in the training set and generalized well to other strings conforming to the grammar and length restrictions. Cluster analyses of the hidden unit patterns showed that they encode prediction-relevant information about the path traversed through the grammar. We provide a description of the different phases of learning, illustrated with cluster analyses, and we note some conditions under which the simple recurrent network will fail to master a set of training sequences.

4:00 **BREAK**

4:20 **O4.4 SHORT-TERM MEMORY AS A METASTABLE STATE: "NEUROLOCATOR," A MODEL OF ATTENTION**

V.I. KRYUKOV, Research Computer Center, USSR Academy of Sciences, Pushchino, Moscow Region

A most important consequence of our theory of phase transitions in the brain is the predictions that CNS contains a phase-locked tracking system for controlling attention and memory in the frequency range of alpha- and theta-rhythms. This paper describes a simplified model of such a system and derives a basic integro-differential equation for its functioning which is almost identical to the equation for the well-known in communication phase-locked loop (PLL). Dynamical properties of this system are shortly discussed to account for the experimental data which are difficult to interpret in terms of the existing models.

4:50 **O4.5 HETEROGENEOUS NEURAL NETWORKS FOR ADAPTIVE BEHAVIOR IN DYNAMIC ENVIRONMENTS**

RANDALL D. BEER, LEON S. STERLING, Departments of Computer Engineering and Science and Center for Automation and Intelligent Systems Research; HILLEL J. CHIEL, Department of Biology and Center for Automation and Intelligent Systems Research, Case Western Reserve University

Recent research in artificial neural networks has generally focused on uniform architectures, i.e., homogeneous networks consisting of simple units with a regular interconnection scheme. In contrast, even simple biological neural networks exhibit great heterogeneity in both their elements and their patterns of interconnection. We argue for heterogeneity in artificial neural networks by describing a simple heterogeneous artificial neural network for controlling the walking of a six-legged "organism" in a simulated environment. This controller is based on the design of neural networks found in biological organisms and is capable of adapting to traumatic changes, such as the removal of a leg, as a natural consequence of its design.

5:20 **O4.6 A LINK BETWEEN MARKOV MODELS AND MULTILAYER PERCEPTRONS**

H. BOURLARD, C.J. WELLEKENS, Philips Research Laboratory, Brussels

In the Hidden Markov Models, commonly used for speech recognition, local probabilities are associated with states or with transitions between states. The incorporation of contextual information or discriminant properties in these probabilities heavily complicates the training algorithm of the models. This problem is circumvented by using a Multilayer Perceptron with feedback to generate highly discriminant and largely context dependent probabilities.

6:30 **RECEPTION (CASH BAR)**

7:30 **CONFERENCE BANQUET**

9:00 **PLENARY SPEAKER: NEURAL ARCHITECTURE AND FUNCTION**

VALENTINO BRAITENBERG, Max Planck Institut fur Biologische Kybernetik, West Germany

THURSDAY AM

ORAL SESSION O5
IMPLEMENTATION

8:30 O5.1 ROBOTICS, MODULARITY, AND LEARNING

RODNEY BROOKS, Artificial Intelligence Laboratory, Massachusetts Institute of Technology

Invited talk.

9:10 O5.2 WINNER-TAKE-ALL NETWORKS OF O(N) COMPLEXITY

J. LAZZARO, S. RYCKEBUSCH, M.A. MAHOWALD, C.A. MEAD, Computational Neural Systems Program, California Institute of Technology

Activity in neural systems is mediated by two general types of inhibition: subtractive inhibition, which may be thought of as setting the zero level for the computation, and multiplicative (non-linear) inhibition which regulates the gain of the computation. We report a physical realization of general nonlinear inhibition in its extreme form, known as *winner-take-all*. We have designed, fabricated, and tested a series of compact CMOS integrated circuits which realize the winner-take-all function. These analog, continuous-time circuits use only O(n) of interconnect to perform this function.

We have also modified this global winner-take-all circuit, realizing a circuit that computes local nonlinear inhibition. Local inhibitory circuits are well suited for use in systems which topographically represent a feature space and which process several features in parallel. We have designed, fabricated, and tested a CMOS integrated circuit which combines the function of the winner-take-all circuit and a nonlinear resistive network to locally compute the winner-take-all function of spatially ordered input. The circuit is composed of a one dimensional array of elements, which interact with *nonlinear lateral inhibition*. Since the competitive interactions are local, multiple winners can occur within the array.

9:40 O5.3 AN ANALOG SELF-ORGANIZING NEURAL NETWORK CHIP

J. MANN, S. GILBERT, Massachusetts Institute of Technology Lincoln Laboratory

A design for a fully analog version of a self-organizing feature map neural network has been completed. Several parts of this design are in fabrication. The feature map algorithm was modified to accommodate circuit solutions to the various computations required. Performance effects were measured by simulating the design as part of a frontend for a speech recognition system. Circuits are included to implement both activation computations and weight adaptation or learning. External access to the analog weight values is provided to facilitate weight initialization, testing and static storage. This fully analog implementation requires an order of magnitude less area than a comparable digital/analog hybrid version developed earlier.

10:10 BREAK

10:30 O5.4 PERFORMANCE OF A STOCHASTIC LEARNING MICROCHIP

JOSHUA ALSPECTOR, BHUSAN GUPTA*, ROBERT B. ALLEN, Bellcore, Morristown, NJ (*permanently at Department of Electrical Engineering, University of California, Berkeley)

We have fabricated a test chip in 2 micron CMOS that can test the function of an electronic parallel network meant to perform supervised learning in a manner similar to the Boltzmann machine. The function of the chip components are explained and the performance is assessed. The chip learns to solve the XOR problem in a few milliseconds. Future plans for scaling the circuit up to useful size are discussed.

11:00 O5.5 A FAST, NEW SYNAPTIC MATRIX FOR OPTICALLY PROGRAMMED NEURAL NETWORKS

C.D. KORNFELD, R.C. FRYE, C.C. WONG, E.A. RIETMAN, AT&T Bell Laboratories, Murray Hill, NJ

We report on the design, construction and operation of a large, optically programmed neural network which uses a new synapse structure that has substantially improved operating characteristics than those reported in our earlier papers. These synaptic arrays are somewhat more difficult to fabricate than our early devices because they require additional photolithography steps and use a dielectric isolation layer. The resulting arrays have symmetric behavior for both activating and inhibiting synapse types. They also exhibit linear response to changes in applied voltage. Preliminary measurements indicate that these devices are nearly 1000 times faster than our earlier devices.

In this paper we will describe these new devices and will compare them to earlier designs. We will also discuss tradeoffs that can be made in the choice of materials and geometries used in these arrays. Next, we will describe how these tradeoffs impact system configurations and potential applications. Finally, we will describe a complete neural network implementation using these new arrays.

11:30 O5.6 PROGRAMMABLE ANALOG PULSE-FIRING NEURAL NETWORKS

ALAN F. MURRAY, Department of Electrical Engineering, University of Edinburgh, Scotland; LIONEL TARASSENKO, Department of Engineering Science, University of Oxford, England; ALISTER HAMILTON, Department of Electrical Engineering, Napier College of Commerce and Technology, Edinburgh, Scotland

We describe pulse - stream firing VLSI devices, supported by digital, on-chip memory for synaptic weights, that form asynchronous, essentially analog neural networks. Synaptic weights are held in off-chip digital RAM, and used to charge on-chip dynamic *analog* storage capacitors through a digital-to-analog converter. Synaptic weighting uses time-division of the neural pulses from a signalling neuron to a receiving neuron. MOS transistors in their "ON" state act as variable resistors to control a capacitive discharge, and time-division is thus achieved by a small synapse circuit cell. The VLSI chip set design uses 3μ CMOS technology.

12:00 POSTER SESSION 2

3:00 ADJOURN TO KEYSTONE FOR WORKSHOP

Author Index